

# Orbital variations in planktonic foraminifera assemblages from the Ionian Sea during the Middle Pleistocene Transition

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## ABSTRACT

The Middle Pleistocene Transition (1.2–0.7 Ma) is the most recent re-organization of the global climate system which includes variations in the frequency and amplitude of glacial/interglacial cycles, increased ice sheet volume, sea surface temperature cooling and a significant drop in the CO<sub>2</sub> atmospheric levels. Here we present high-resolution planktonic foraminifera data (mean sampling resolution of about 780 years) from core LC10 recovered in the Ionian Sea (eastern Mediterranean), between 1.2 and 0.9 Ma. Selected taxa, among them *G. ruber*, *T. quinqueloba* and *G. bulloides*, show significant periodicities that can be associated to orbital cycles, mainly precession and obliquity. The planktonic foraminifera based paleoclimatic curve exhibits a cooling linear trend that can be associated to similar phenomena observed in the North Atlantic. On the other hand, we refer to the influence of the North African Monsoon the occurrence of two peaks of the low-salinity tolerant species *G. quadrilobatus* that fall in coincidence of sapropel layers. Finally, we discuss the distribution pattern of *N. pachyderma* sinistral coiling, with peaks up to about 20% between MIS 30 and 28, and compare it to middle-late Quaternary records of the Sicily Channel and western Mediterranean.

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## 1. Introduction

The Middle Pleistocene Transition (MPT) that lasted from 1.2 to 0.7 million years ago, is the most recent re-organization of the global climate system. Glacial/interglacial cycles with 100-kiloyear (kyr) pacing replaced lower amplitude 41-kyr cycles without a modification in the Earth's orbital parameters (Pisias and Moore, 1981; Lisiecki and Raymo, 2005). Researchers have documented a series of phenomena associated to the MPT: an increase in ice sheet volume, sea surface temperature (SST) cooling in the oceans, variations in the Atlantic Meridional Overturning Circulation (AMOC), a significant drop in the CO<sub>2</sub> atmospheric levels, stronger African and Asian monsoon activity and increased dust deposition in the Southern Ocean (e.g. Ruddimann et al., 1989; Mix et al., 1995; Venz and Hodell, 2002; Hodell et al., 2003; Schefus et al., 2004; Lisiecki and Raymo, 2005; McClymont and Rosell-Melè, 2005; Clark et al., 2006; Sun et al., 2006; Martínez-García et al., 2011).

A high sensitivity of the Mediterranean Sea to orbital and suborbital climatic variations has been proven, even for late Quaternary abrupt changes (e.g. Lourens et al., 1996; Martrat et al., 2004; Sprovieri et al., 2006; Incarbona et al., 2008a). The Mediterranean basin climate is characterized by global scale connections. The descending branch of the

Hadley circulation affects the area in summer and is coupled to the zonal tropical circulation which is interconnected with the Indian and African Monsoon. Westerlies prevail during the winter season and their track and strength is mostly controlled by the North Atlantic Oscillation (Bolle, 2003).

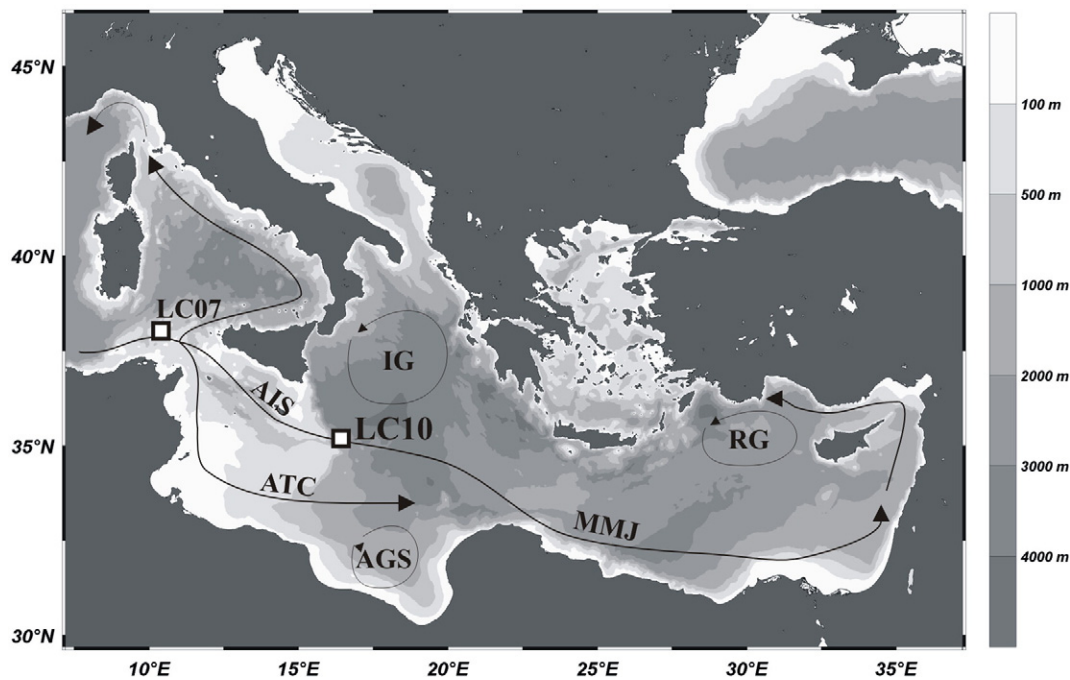
The Mediterranean Sea is ideally located to reveal climatic system interplays during the MPT. However, only a few studies focused on this region, analysing the response of the vegetational patterns, calcareous nannofossils and oxygen isotopes (Maiorano and Marino, 2004; Maiorano et al., 2004; Joannin et al., 2008, 2011; Marino et al., 2008; Ciaranfi et al., 2010). Here we show high-resolution (~780 years) data of planktonic foraminifera assemblages, in order to investigate the evolution of surface water characteristics, mainly in terms of SST and productivity. We examine the periodicity of abundance variations recognized in selected taxa, in comparison with orbital parameters. Finally, we try to assess the impact of different climate systems in the Ionian Sea surface water during the MPT.

## 2. Materials and Methods

Core LC10 (35°12.77'N; 16°34.88'E) was recovered by the R/V Marion Dufresne in 1995, from a bank north of Heron Valley in the Ionian Sea, at a depth of 1322 m (Fig. 1). The core consists of about 20 m of greyish yellow olive grey foraminifer-rich mud and nannofossil ooze. A thin tephra layer is located at about 4.55 m below sea floor (mbsf),

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**Fig. 1.** Bathymetric map of the central-eastern Mediterranean Sea and location of core LC10 and core LC07 (white squares). Black arrows show the path of surface circulation, while three of the most important semi-permanent mesoscale features are also shown. AIS, Atlantic-Ionian Stream. ATC, Atlantic Tunisian Current. MMJ, Mid-Mediterranean Jet. IG, Ionian Gyre, showed as a cyclonic configuration, following its most recent shift (Civitarese et al., 2010). AGS, Anticyclone in the Gulf of Syrte. RG, the cyclonic Rhodes Gyre (modified from Pinardi and Masetti, 2000).

while several dark sapropelitic layers have been recognized in the sedimentary sequence. Three of them are within the investigated interval, at about 16.50, 18.00 and 18.60 mbsf (Dinarès-Turell et al., 2003).

Planktonic foraminifera were studied every 1 cm in the interval between 19.82 and 15.87 mbsf. Samples were dried and washed on a 63  $\mu\text{m}$  sieve. The relative abundance of each species was obtained from splits of about 300 specimens, in the residue greater than 125  $\mu\text{m}$ . Fifteen species or species groups were distinguished, following Bolli et al. (1985) and Hemleben et al. (1989) taxonomic concepts. *Globigerinoides ruber* includes *Globigerinoides elongatus*. *Globigerinoides quadrilobatus* includes *Globigerinoides trilobus* and *Globigerinoides sacculifer*. *Globigerina bulloides* includes *Globigerina falconensis*. The paleoclimatic curve presented here is the algebraic sum of warm-water species percentages (*G. ruber*, *Hastigerina siphonifera*, *G. sacculifer*, *Globoturborotalita rubescens* and *Globoturborotalita tenella*) expressed as positive values and cold-water species percentages (*Neoglobobulimina pachyderma*, *G. bulloides*, *Turborotalita quinqueloba*, *Globorotalia scitula* and *Globigerinita glutinata*) expressed as negative values (Corselli et al., 2002; Sprovieri et al., 2006; Incarbona et al., 2010). In fact, among others, *G. ruber* ecological preference for warm and oligotrophic surface waters has been established in numerous oceanographic settings (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Žarić et al., 2005) and paleoceanographic reconstructions (Sprovieri et al., 2003, 2006, 2012); *T. quinqueloba* thrives in cold and nutrient-rich surface waters (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Žarić et al., 2005); *N. pachyderma* lives in cold waters of middle-high latitude and is a proxy for deep chlorophyll maximum levels (e.g. Rohling and Gieskes, 1989).

Calcareous nannofossil analysis was carried out by observation with a polarized microscope at about 1000 $\times$  magnification, sampling every 10 cm between 17.60 and 16.50 mbsf. Rippled smear slides were prepared following the standard procedure (Bown and Young, 1998). Two counting methodologies were applied to detect the re-entrance of medium-sized *Gephyrocapsa* event: the analysis of 5000 specimens of the whole assemblage and the analysis of 100 specimens within the genus *Gephyrocapsa*.

The 'REDFIT' power spectrum (Schulz and Mudelsee, 2002), a modified version of the Lomb–Scargle periodogram (Lomb, 1976; Scargle, 1982), was used to search possible periodicities recorded in the nonuniformly sampled signal of planktonic foraminifera species. A first-order autoregressive process (AR1) was carried out by REDFIT directly from unevenly spaced time series without requiring interpolation, to test if peaks of the signals are significant against the red-noise background.

Magnetic measurements were carried out every 1 cm with a 2-G Enterprises cryogenic magnetometer fitted with an inline coil to measure magnetic susceptibility. Since no additional analyses were carried out in the present paper, we refer to Dinarès-Turell et al. (2003) where magnetic measurements methodology for core LC10 is widely discussed.

### 3. Study area

Surface waters, called Modified Atlantic Water (MAW), enter the eastern Mediterranean Sea from the Sicily Channel (Fig. 1) and occupy the first 100–200 m of the water column. In particular, the northern branch of the Sicily Channel stream, called the Atlantic Ionian Stream (AIS), contributes to the MAW transport into the eastern Mediterranean off the southern coast of Sicily (Robinson et al., 1999; Béranger et al., 2004). AIS meanders into the Ionian Sea and feeds the mid-Mediterranean jet that flows in the central Levantine basin up to Cyprus (POEM group, 1992; Pinardi and Masetti, 2000).

Levantine Intermediate Water (LIW) forms in the eastern basin in February–March as a process of surface cooling on water masses which underwent a severe salt enrichment in the area between Rhodes and Cyprus (Ovchinnikov, 1984). LIW occupies a depth between 150–200 and 600 m and is prevalent and ubiquitous throughout the Mediterranean Sea, contributing to the dense water formation in the northern part of the basin (POEM group, 1992; Millot, 1999).

Dense water forms in the northern part of the eastern basin (Eastern Mediterranean Deep Water—EMDW), in the Adriatic and Aegean Sea and is preconditioned by the presence of permanent cyclonic

gyres (Fig. 1). The detailed formation process is not well known and understood. It starts with the blowing of very cold and dry air masses (Bora and Etesian) which cause deep convection throughout the water column. Sunken surface water admixes with LIW and fills the sea bottom. In the case of the Adriatic Sea, the newly formed EMDW exits through the Strait of Otranto and plunges to the deep western boundary of the Ionian basin (POEM group, 1992).

The trophic resources of the Mediterranean Sea are among the poorest in the world's oceans and the anti-estuarine circulation pattern contributes to its maintenance (Bethoux, 1979; Sarmiento et al., 1988). Primary production is controlled by the seasonal dynamics of the water column, with biomass increase in late winter/early spring and very low values in summer (Morel and André, 1991; Antoine et al., 1995; Bosc et al., 2004; D'Ortenzio and Ribera d'Alcalà, 2009). There is a significant west–east trophic gradient, with a reduction in primary productivity in the eastern basin of over a factor of three (Bosc et al., 2004; D'Ortenzio and Ribera d'Alcalà, 2009), which follows the same increasing nutrient depletion trend, particularly exacerbated for phosphorus (Krom et al., 1991, 2010). Productivity estimates of the Ionian Sea suggest that it is the most oligotrophic subbasin together with the Levantine Sea (Antoine et al., 1995; D'Ortenzio et al., 2003; Bosc et al., 2004). Moreover, primary productivity reflects the hydrological fragmentation due to mesoscale variability. Core LC10 is only a few tens of kilometres from the Ionian Gyre (Fig. 1) which seems to switch from a cyclonic to an anticyclonic configuration at a decadal scale, affecting the biological productivity in the northern Ionian and southern Adriatic Sea (Civitarese et al., 2010; Gačić et al., 2010).

#### 4. Age model

It has been shown that a climatic forcing mechanism controls the rock magnetic signature in cores LC07 (western Sicily Channel) and LC10 (Dinarès-Turell et al., 2003, 2002). The variations appear to be related to the magnetite grain size, with glacial periods dominated by the relatively coarse magnetite grains due to enhanced African dust input, alternating with fine-grained magnetite formed by magnetotactic bacteria during interglacials. In particular, in core LC07 (Fig. 1), the validity of the age model construction has been supported by the analysis of oxygen isotopes and calcareous planktonic assemblages (Incarbona et al., 2008b).

A slight modification to the LC10 age model, as originally proposed by Dinarès-Turell et al. (2003), has been carried out: the tuning of the magnetic susceptibility was performed on the more recent 'LR04' benthic stack (Lisiecki and Raymo, 2005). The negative peak of magnetic susceptibility interpreted as MIS 27 by Dinarès-Turell et al. (2003) was shifted down, to include the light values peak of MIS 28 in the 'LR04' benthic stack (Fig. 2). A linear interpolation has been carried out among the adopted tie-points, that is MISs transition mid-points, listed in Table 1.

A further control on the validity of the age model was provided by the calcareous nannofossil biostratigraphy. The re-entrance of medium-sized *Gephyrocapsa*, that marks the MNN19f zone (Rio et al., 1990), has been recognized at 16.90 mbsf, counting 5000 coccoliths, in the lower part of MIS 26 (Fig. 2). The same event has been found at 16.60 mbsf with the analysis of 100 *Gephyrocapsa* spp. specimens, that is within MIS 25. In any case, this bioevent falls within the interval MIS 26/MIS 25, in agreement with other reports from the eastern Mediterranean Sea (Raffi, 2002; Maiorano and Marino, 2004).

The sedimentation rates show a mean value of 1.29 cm/kyr (Fig. 3) which is comparable to other Middle Pleistocene records in the Ionian Sea (e.g. Sprovieri et al., 1998; Lourens, 2004; Di Stefano and Incarbona, 2008). In spite of the very detailed sampling strategy (every 1 cm), the resolution of planktonic foraminifera data spans from about 510 years to 1330 years (Table 1), with a mean value of 776.8 years.

#### 5. Results

Planktonic foraminifera shells in core LC10 are well preserved and the assemblages are well diversified. About 20 taxa have been identified, but only *G. ruber*, *T. quinqueloba*, *G. bulloides*, *G. inflata* and *Orbulina* spp. show repeated abundance fluctuations that are associated with glacial/interglacial cycles (Fig. 4). *G. quadrilobatus* exhibits three distinctive peaks at the transition of MISs 35/34, MISs 31/30 and MISs 25/24 (Fig. 4). *N. pachyderma* dx is more abundant since the base of MIS 30, while *N. pachyderma* sx is mostly limited between MISs 30 and 28 (Fig. 4).

The planktonic foraminifera paleoclimatic curve shows repeated negative (cold surface water) and positive (warm surface water) fluctuations which are usually linked to respectively even and odd MISs. Sometimes, two or three warm water peaks have been recognized within the longest MISs, such as MIS 35 and 25 (Fig. 2), possibly following the division in substages. In addition, we argue that high-frequency switches today observed in the oceanographic mesoscale feature of the Ionian Sea (Civitarese et al., 2010) may have acted in the past, affecting the thermal character of surface water, for instance by upwelling phenomena during the cyclonic configuration.

The spectral analysis demonstrates the occurrence of periodicities, over the 95% confidence level, in all selected taxa. Cycles close to 19–23 kyr and to 40 kyr have been found for instance in the planktonic foraminifera paleoclimatic curve, *G. bulloides*, *Orbulina* spp., *T. quinqueloba* and *G. ruber* (Fig. 5). In addition, the planktonic foraminifera assemblages display other significant periodicities at about 30 kyr, 50 kyr, 60 kyr and 80 kyr (Fig. 5).

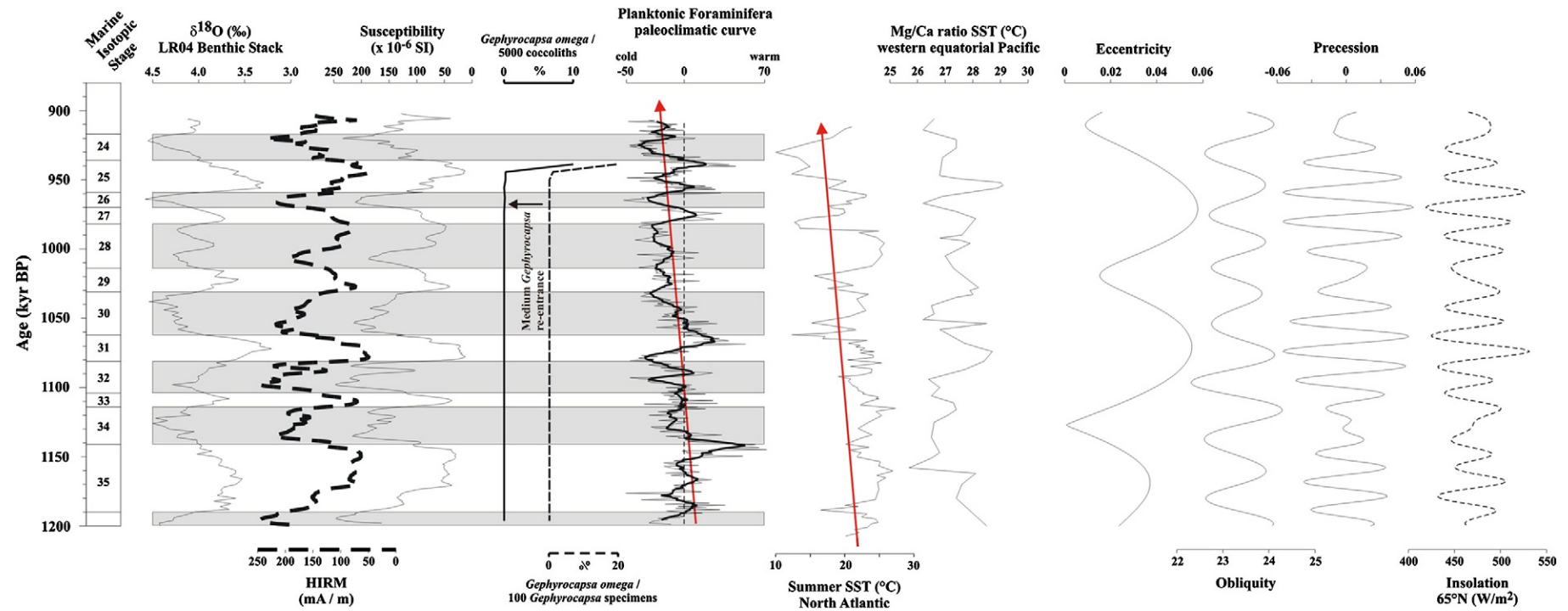
#### 6. Discussion

##### 6.1. The influence of the North Atlantic climate system and of the African Monsoon

The magnetic susceptibility record at site LC10 is interpreted as a proxy for Saharan dust deposition and, indirectly, to the monsoon activity strength (Dinarès-Turell et al., 2003). The highest values, associated with even MISs, may be the result of increased dust deposition due to the aridity in North African regions which led to a reduced vegetation and an increased erosion (deMenocal, 1995, 2004; Dinarès-Turell et al., 2003). The spectral analysis shows a major periodicity centred at about 40 kyr and a weaker one at about 20 kyr, respectively tied to the obliquity and precession cycles (Fig. 5), like other records in the eastern Mediterranean and the western African margin during the MPT (deMenocal, 1995; Larrasoña et al., 2003; deMenocal, 2004; Trauth et al., 2009).

The LR04 benthic stack curve shows the same linear trend towards heavier oxygen isotopic values (Fig. 2) and the same periodicities linked to obliquity and precession (Fig. 5) have been observed in the North Atlantic Ocean (e.g. Ruddiman et al., 1989; Raymo et al., 1990; Tiedemann et al., 1994; Kleiven et al., 2003; Clark et al., 2006).

Most of the selected planktonic foraminifera taxa at site LC10 show significant periodicities linked to the obliquity and to the precession (Fig. 5). Also the cycles of about 30 kyr, 50 kyr, 60 kyr and 80 kyr commonly found in other paleoclimatic records, can be ascribed to the interaction among, or to a multiple of, primary orbital periods (e.g. Negi and Tiwari, 1984; Rea, 1994; Huybers and Wunsch, 2005; Tziperman et al., 2006; Marino et al., 2009). Thus it is very hard to distinguish between the African Monsoon and the North Atlantic climate system influence in the eastern Mediterranean record on the basis of the spectral analysis. However, we argue that a clue of the contribution of these two climate systems can be deduced by considerations on the Sea Surface Temperature (SST) and the ecological preference and biogeographical distribution of some taxa, specifically *N. pachyderma* sx (see Section 6.2 below) and *G. quadrilobatus*.



**Fig. 2.** Downcore tuned variations of magnetic properties, planktonic foraminifera paleoclimatic curve and distribution pattern of *G. omega* at LC10 site, in comparison with oceanic records and orbital parameters. From the left, the  $\delta^{18}\text{O}$  LR04 benthic stack (Lisiecki and Raymo, 2005); magnetic properties (HIRM and susceptibility) measured in core LC10 and used for the age model assessment; the relative abundance (%) of *G. omega* evaluated versus 5000 coccoliths (thick line) and 100 *Gephyrocapsa* spp. specimens (thick dashed line); the planktonic foraminifera paleoclimatic curve. The thick line represents a 3-point running average. The red arrow indicates the linear cooling trend; SST ( $^{\circ}\text{C}$ ) estimates by planktonic foraminifera census data in the North Atlantic (Ruddiman et al., 1989). The red arrow indicates the linear cooling trend; SST ( $^{\circ}\text{C}$ ) estimates by Mg/Ca ratio in the western equatorial Pacific (de Garidel-Thoron et al., 2005); orbital parameters and summer insolation at  $65^{\circ}\text{N}$  (Laskar et al., 2004). Light grey and white bands represent the alternation of respectively even (glacial) and odd (interglacial) MISs.

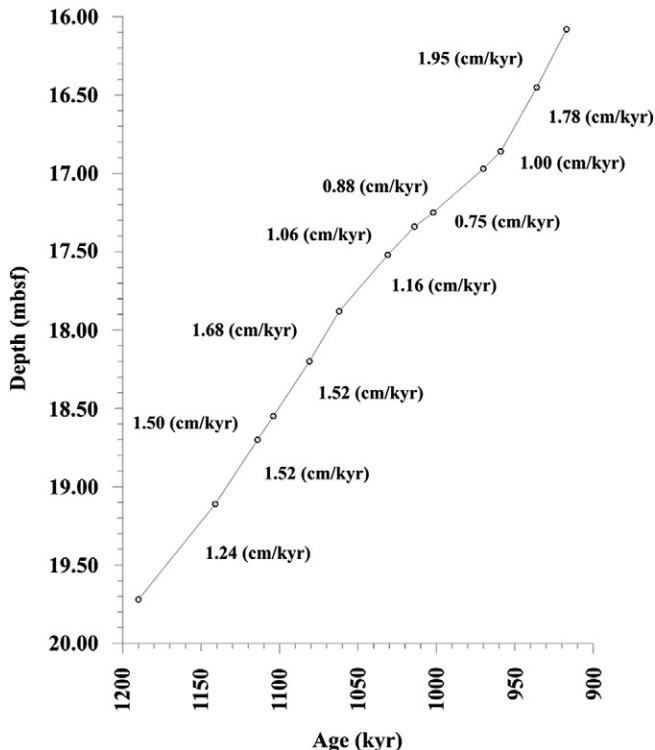


**Table 1**

Data used for the age model construction. From the left, marine isotopic stage boundaries. Note that the asterisk in the 28/27 boundary indicates that it was shifted down to include the light values peak of MIS 28 (see Chapter 4 and Fig. 2); ages (kyr) imported from the  $\delta^{18}\text{O}$  LR04 benthic stack (Lisiecki and Raymo, 2005); depth (mbsf) of MISs at core LC10, recognized on the basis of magnetic susceptibility data (Dinarès-Turell et al., 2003); sedimentation rates (cm/kyr) calculated on the basis of linear interpolation between the adopted tie-points and the subsequent sampling resolution (years).

MIS boundary	Age (kyr)	Depth (mbsf)	Sedimentation rate (cm/kyr)	Sampling resolution (1 cm)
24/23	917	16.08		
24			1.95	513.5
25/24	936	16.45		
25			1.78	561.0
26/25	959	16.86		
26			1.00	1000.0
27/26	970	16.97		
27			0.88	1142.9
28/27*	1002	17.25		
28			0.75	1333.3
29/28	1014	17.34		
29			1.06	944.4
30/29	1031	17.52		
30			1.16	861.1
31/30	1062	17.88		
31			1.68	593.7
32/31	1081	18.20		
32			1.52	657.1
33/32	1104	18.55		
33			1.50	666.7
34/33	1114	18.70		
34			1.52	658.5
35/34	1141	19.11		
35			1.24	803.3
36/35	1190	19.72		

The latter species lives in warm surface waters characterized by relatively lower salinity (Bé and Tolderlund, 1971; Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Sprovieri et al., 2003). In



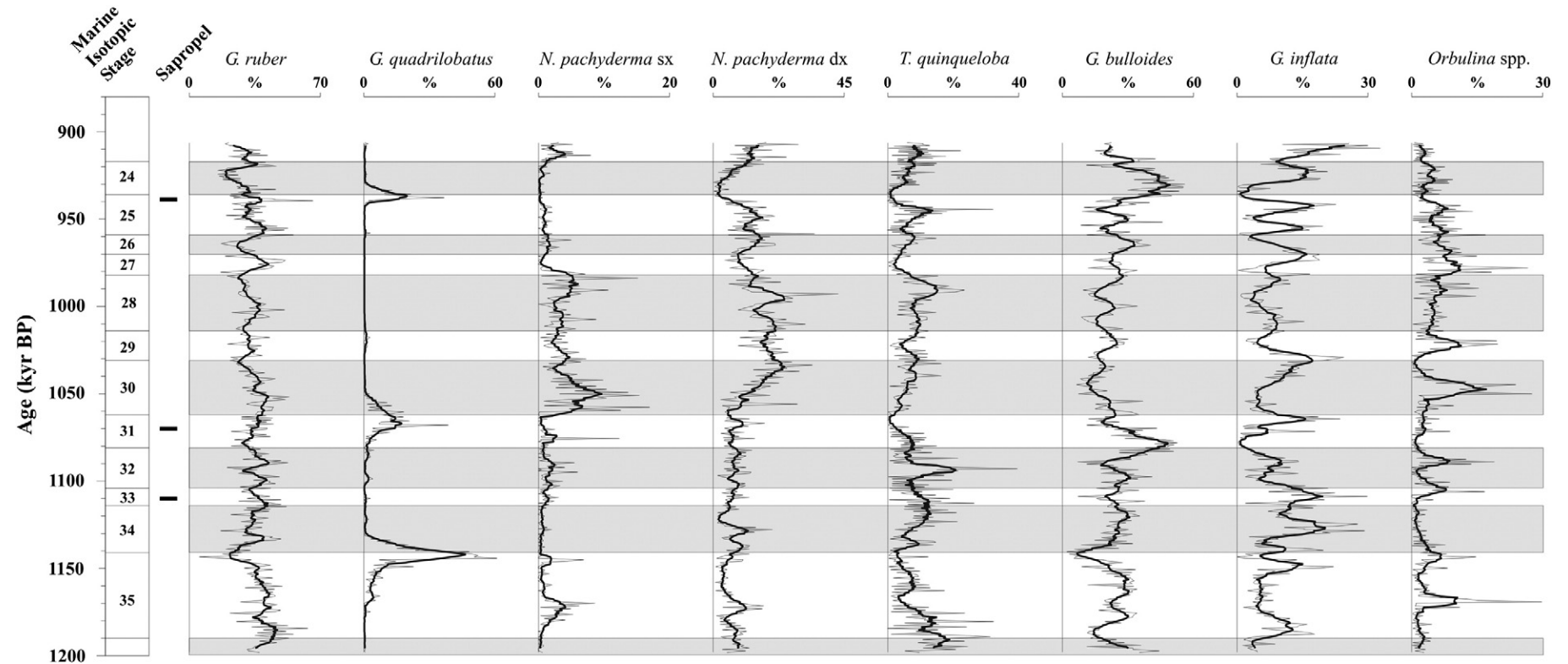
**Fig. 3.** Age (kyr) versus depth (mbsf) plot of core LC10. Open circles indicate the adopted tie-points, while sedimentation rate values of the different segments are also indicated.

the LC10 record, two distinctive peaks of *G. quadrilobatus* coincide with two sapropel layers, at about 1070 kyr and 940 kyr (Fig. 4). Several hypotheses have been formulated for the development of bottom anoxia in the Eastern Mediterranean Sea, mainly linked to higher productivity levels and the weakening/interruption of deep water formation (Rohling, 1994; Cramp and O'Sullivan, 1999). In any case, the exceptional African Monsoon activity, and the consequent strong Nile (and other presently buried North African) river runoff, was a prime forcing factor of this phenomenon (Rossignol-Strick, 1983, 1985; Hilgen, 1991; Lourens et al., 1996; Rohling et al., 2002a, 2004; Marino et al., 2007, 2009). Thus, the two peaks of *G. quadrilobatus* may be an indirect response to the tropical climate influence. However, the oldest, and most pronounced, peak of *G. quadrilobatus* occurs at about 1145 kyr. The grey reflectance analysis did not record any significant darkening in coincidence of this interval (Dinarès-Turell et al., 2003), but the timing of this horizon is suspect, given that at Ocean Drilling Program (ODP) Site 967 a red interval was noticed (Emeis et al., 2000). Trace element analysis, and especially the Ba/Al profile, would be needed to clarify the original nature of sediments deposited at LC10 site 1145 ka. Finally, we note that there is no any significant abundance increase of this species at about 1110 kyr, when the third sapropel was deposited (Fig. 4). This behaviour may be due to the increased importance of factors, other than Nile river runoff, for the formation of this sapropel layer, such as primary productivity (e.g. Calvert et al., 1992). Alternatively, ecological factors like SST and food availability may have limited the *G. quadrilobatus* population, regardless of sea surface salinity.

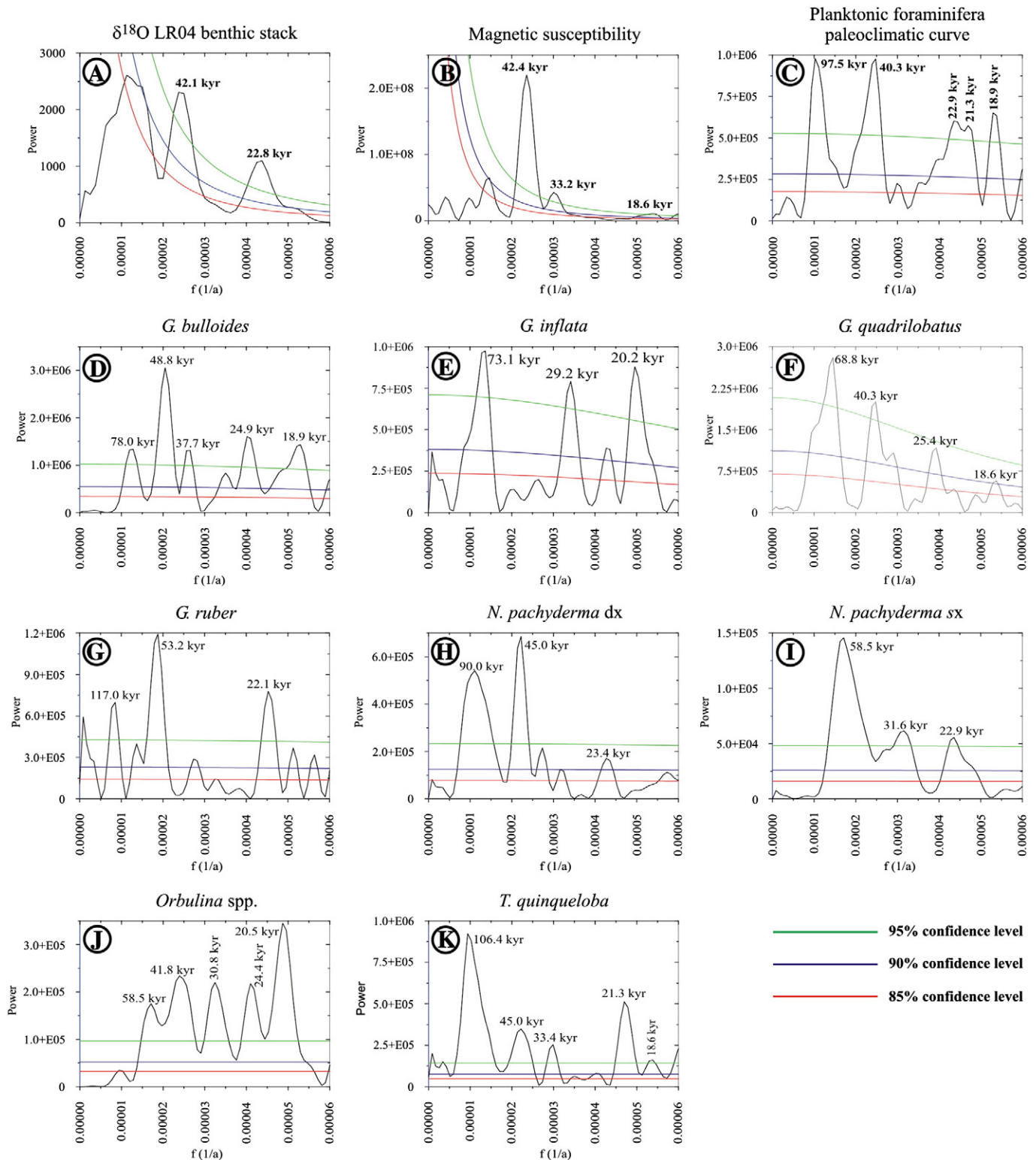
The planktonic foraminifera paleoclimatic curve indicates an obvious pattern of warm oligotrophic water during odd MISs and cold and more productive water during even ones. The power spectrum of this curve shows significant periodicities tied to precession, obliquity and surprisingly also to eccentricity (about 100 kyr) that is not captured by the magnetic susceptibility record at site LC10 and by the LR04 benthic stack curve (Fig. 5). However, we point out that the linear trend of cooling in the Ionian Sea surface waters during the MPT seems to parallel Atlantic Ocean records, whilst contrasting evidence on the SST trends exists in the Pacific Ocean (Fig. 2) (Ruddiman et al., 1989; Marlow et al., 2000; Schefus et al., 2004; de Garidel-Thoron et al., 2005; McClymont and Rosell-Melè, 2005; Clark et al., 2006). Teleconnection phenomena between the Mediterranean and the Greenland/North Atlantic region are documented for the late Quaternary (e.g. Rohling et al., 1998; Cacho et al., 1999; Sbaifi et al., 2001; Rohling et al., 2002b; Sprovieri et al., 2003; Martrat et al., 2004; Pérez-Folgado et al., 2004; Sprovieri et al., 2006; Incarbona et al., 2008a). This connection has been explained by variations in North Atlantic Deep Water formation rate, as modelling experiments suggest that this mechanism is able to cause coherent temperature changes in the two regions (e.g. Manabe and Stouffer, 1997; Vellinga and Wood, 2002). Thus, we refer the cooling trend observed in our record to the influence of the northern climate system and specifically to the Atlantic Meridional Overturning Circulation and North Atlantic SST.

## 6.2. The distribution of *N. pachyderma* sx

The first appearance of the modern-type of *N. pachyderma* sx specimens, that can be used as a paleotemperature proxy, occurred about 1250 kyr ago in the oceans (Kucera and Kennett, 2002). Thus, the significant pulsation of this species in the Ionian Sea record between MIS 30 and 28 (Fig. 4) is a real evidence of severe cold surface water. It is striking the relative abundance magnitude, up to about 20% (Fig. 4), in comparison with its rarity (<5%) in the central/eastern Mediterranean during the late Quaternary (e.g. Thunell, 1978; Rohling and Gieskes, 1989; Rohling et al., 1993; Hayes et al., 1999; Sprovieri et al., 2003; Hayes et al., 2005; Triantaphyllou et al., 2009; Siani et al., 2010; Sprovieri et al., 2012). This situation is well illustrated by the long-range study of ODP Site 964, drilled in the Ionian Sea



**Fig. 4.** Downcore variations of the relative abundance (%) of selected planktonic foraminifera taxa at LC10 site. The thick lines represent 3-point running averages. Light grey and white bands represent the alternation of respectively even (glacial) and odd (interglacial) MISs. The three sapropel layers recognized in the studied interval by grey reflectance analysis (Dinarès-Turell et al., 2003) are showed as thick black segments.



**Fig. 5.** Spectral analysis of the (A)  $\delta^{18}\text{O}$  LR04 benthic stack (Lisiecki and Raymo, 2005), (B) magnetic susceptibility at LC10 site (Dinarès-Turell et al., 2003), (C) planktonic foraminifera paleoclimatic curve and (D–F) selected planktonic foraminifera taxa. Green, black and red curves indicate confidence levels at respectively 95, 90 and 85%.

(Sprovieri et al., 1998). Peaks of about 25% of *N. pachyderma* sx occur within the nannofossil Zones MNN19e and MNN19f, that is around the MPT, while there is a general decrease and rarity above at that site. Interestingly, *N. pachyderma* sx shows the same long-range distribution pattern in the western Mediterranean. Peaks in abundance

up to 80–90% are recorded at ODP sites 976 (Alboran Sea) and 975 (Balearic Rise), again between MNN 19e and MNN 19f Zones (Linares et al., 1999). Thereafter, in the western Mediterranean Sea several fluctuations with maxima values of 20% have been documented in coincidence of Heinrich events, during the last glacial periods



(Rohling et al., 1998; Cacho et al., 1999; Pérez-Folgado et al., 2003; Sierro et al., 2005), and interpreted as the entrance of this species into the Mediterranean Sea during the southward shift of the Polar Front in the North Atlantic during the slow-down of North Atlantic Deep Water (NADW) formation.

We argue that the lower abundance of *N. pachyderma* sx in both the eastern and the western Mediterranean Sea after the MPT is paradoxical, since colder conditions and a much thicker ice accumulation in Greenland and Antarctica sheets are documented (Lisiecki and Raymo, 2005). Even the oceanographic process that leads to the entrance of *N. pachyderma* sx into the Gibraltar Strait during the cold spells of the Late Quaternary is not suitable as an analogue for the MPT, since the whole North Atlantic shows high  $\delta^{13}\text{C}$  values, with very low glacial/interglacial variability that testifies to intense and persistent NADW formation (Raymo et al., 1990; Venz and Hodell, 2002; Kleiven et al., 2003; Clark et al., 2006). Further high-resolution studies would be needed to clarify the climatic/oceanographic forcing that controls the distribution and the dispersal of *N. pachyderma* sx in the Mediterranean basin during the middle-late Quaternary.

## 7. Conclusion

High-resolution planktonic foraminifera data, collected every ~780 years, from core LC10 recovered in the Ionian Sea allowed us to speculate on the surface marine ecosystem evolution during the MPT, between 1.2 and 0.9 Ma. Selected taxa, such as *G. ruber*, *G. bulloides*, *G. inflata* and *T. quinqueloba*, show significant periodicities that can be ascribed to orbital climate forcing. Cycles close to 19–23 kyr and to 40 kyr can be respectively ascribed to precession and obliquity, whereas other significant periodicities at about 30, 50, 60 and 80 kyr are best explained as the result of the interaction among primary orbital periods. Since obliquity and precession are the main periodicities also found in the North Atlantic oxygen isotopes (Ruddimann et al., 1989; Raymo et al., 1990; Tiedemann et al., 1994; Kleiven et al., 2003; Clark et al., 2006) and in the proxy curves of the African Monsoon intensity (deMenocal, 1995, 2004; Trauth et al., 2009), the spectral analysis of planktonic foraminifera assemblages at LC10 site is not able to determine the contribution of these two climate forcings.

The planktonic foraminifera paleoclimatic curve shows a cooling linear trend that can be correlated to a similar trend in the SST records of the North Atlantic (Ruddimann et al., 1989; Marlow et al., 2000; Schefus et al., 2004; Clark et al., 2006) and can be interpreted on the basis of teleconnection between the two regions. Two distinctive peaks of *G. quadrilobatus*, in coincidence of sapropel layers, may be the response to North African river runoff in the eastern Mediterranean and to the exceptional monsoon activity. Thus, at least in these two cases, we suggest that planktonic foraminifera assemblages may discriminate the main contribution of the North Atlantic climate system and the African monsoon on the eastern Mediterranean Sea marine environment.

Finally, we found a significant high relative abundance (up to 20%) of the polar species *N. pachyderma* sx between MIS 30 and 28, that is striking in light of its very rare occurrence in the late Quaternary records of the central and eastern Mediterranean Sea (Thunell, 1978; Rohling and Gieskes, 1989; Rohling et al., 1993; Hayes et al., 1999; Sprovieri et al., 2003; Hayes et al., 2005). We argue that more data would be needed to understand the meaning of the distribution pattern of *N. pachyderma* sx and its dispersal into the Mediterranean Sea since the MPT.

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